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The main technical achievement of the project was the development of a comprehensive vector Maxwell unidirectional laser pulse propagator to accurately simulate intense ultra-short atmospheric light strings, white-light super-continuum generation across a broad landscape of applications, short range THz emission from plasma channels left in the wake of critically-collapsing light strings, nonlinear X- and O-wave generation in air, water and condensed matter and super-continuum shaping in sub-micron diameter fiber cores and photonic crystal fibers. The propagator model is broadly inclusive, allowing for the first time the capability to propagate optical carrier resolved, 3D space and time laser pulses over many meter distances. Furthermore it allows seamless transition to all known prior ultra-short pulse propagators in the literature thereby clearly identifying the physical limitations of each. Funding from the project also enabled the initial development of a full 3D FDTD vector Maxwell space and time grid refinement algorithm. It is anticipated that the propagator developed in this project will need to be fully interfaced to a Maxwell solver in anticipation of future extreme nonlinear optics applications.

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# Final Technical Report

# Computational Nonlinear Optics: Femtosecond Atmospheric Light String Applications

**Grant #: AFOSR F49620-03-1-0194**

**Grant Period : January 1, 2003 – December 31, 2005. No-cost extension to June 29, 2006.**

**Principal Investigator : J.V. Moloney**

## Project Goals

The key goal of this project was to provide a rigorous theoretical and computational framework to check the feasibility of various applications in atmospheric light string and other nonlinear optical propagation phenomena requiring resolution of extremely fine features. Fully "optical carrier resolved" vector femtosecond pulse propagators will provide the basis for investigating a broad landscape of nonlinear optical interactions including: white-light super-continuum generation due to electromagnetic optical shocks, directionally narrow white-light scattering from water droplets, backward Raman generation. Research would be carried out into deriving more realistic physical material interaction models appropriate to femtosecond-duration pulse interactions.

The project proposed a multi-disciplinary collaboration with the experimental group of Professor J.C. Diels at the University of New Mexico, with Dr. James Murray of Lite Cycles, Tucson and with Professor FHM Faisal and Dr. Andreas Becker at the University of Bielefeld, Germany. The collaboration with the experimental group of Professor Diels was to provide an experimental validation route to the modeling. Dr. Murray acted as a project consultant providing input on potential Air Force applications. Professor Faisal and Dr. Becker are world experts on *ab initio* calculations of ultra-intense laser pulse interactions with molecules, including $N_2$, and $O_2$, key constituents of air.

Supplemental funding was added to the original grant to carry out a one-year study of the feasibility of selectively ablating aircraft engine turbines as a means of healing microscopic cracks. A technical report "Ultrafast Laser Pulse Machining of Coated Nickel-Base Alloy " was submitted to the Air Force on completion of this project in 2004.

A parallel effort was initialized in computational nanophotonics in anticipation of the need to eventually interface the pulse propagators to Maxwell FDTD solvers. Uniform/ non-uniform mesh and an adaptive space and time 3D FDTD solvers were developed. A

goal here was to better understand ultrashort pulse interaction with dielectric disks and spheres as a prelude to studying water droplets.

## Executive Summary

The continued success enabled by this grant maintains researchers at the Arizona Center for Mathematical Sciences (ACMS) at the forefront worldwide in modeling ultra-short intense laser pulse propagation in various linear and nonlinear media. The large number of publications in Physical Review Letters and other top quality journals as a consequence of the research generated under is project, is testament to the high regard of the work in the eyes of the international community. The key breakthrough result was the publication of the paper "Unidirectional pulse propagation equation" by M. Kolesik, J.V. Moloney and M. Mlejnek in Physical Review Letters, **89**, 2839021 (2002). This work on UPPE laid the foundation for the many successful achievements of the present grant and provided the first, fully-carrier resolved, unidirectional vector pulse propagator that could evolve 3D arbitrarily shaped laser pulses over many meter distances. Moreover, this UPPE model provided the first systematic means of transitioning seamlessly to the famous Nonlinear Schrödinger Equation pulse propagation model and to the many more recent propagation models proposed as an improvement on NLSE. In stark contrast, 3D FDTD Maxwell solvers are so computationally intensive that they are restricted to fine three-dimensional domains spanning typical computational volumes of dimension $100\mu m \times 100\mu m \times 1000\mu m$. FDTD vector Maxwell solvers are further restricted in application by the rather simplistic, spectrally local, single and multiple pole Lorenz light-matter models. United States Air Force Captain Thomas Niday, completed his Ph.D studies in Optical Sciences at the University of Arizona working directly on this project. The title of his Ph.D Thesis is entitled "Stability and Transient Effects in Ultrashort UV Filaments". Dr. Niday successfully defended his Ph.D on July 15, 2005.

The first significant application of UPPE under this project was to atmospheric light string propagation. The complex nonlinear physics occurring in the intense focal region of the critically-self-focused pulse (white-light supercontinuum generation spanning the entire UV – IR spectrum, optical breakdown of air with plasma generation that blue-shifts the supercontinuum and emits an intense burst of THz short range radiation from the recombining plasma) necessitates a nonlinear pulse propagator that can resolve light-matter coupling over these huge spectral ranges. The experimental team of Professor Diels at UNM were tasked with setting up light string experiments in the UV. Because of technical details and lack of specialized hardware resources, this effort was not productive and terminated after one year. Dr. James Murray remained as consultant on the project in spite of his moving from Lite Cycles to Arete Associates in 2004.

# Technical Report

In this AFOSR funded project "*Computational Nonlinear Optics: Femto Atmospheric Light String Applications*" AFOSR F49620-03-1-0194, we further developed and demonstrated a novel ultrashort unidirectional, optical carrier-resolved, vector pulse propagator (UPPE). The development of this model was necessary because of the obvious shortcomings of classical nonlinear envelope pulse propagation models such as Nonlinear Schrödinger Equation (NLSE) and its many variants when applied to ultrashort, high intensity pulse propagation phenomena in bulk media. The NLSE is a slowly varying envelope propagator for near paraxial pulses that necessarily is restricted to spectrally narrow nonlinear excitations. A detailed derivation of NLSE with higher order corrections, as an asymptotic expansion in a small parameter can be found in the textbook *Nonlinear Optics* by Moloney and Newell [Moloney2004]. It was recognized that newly emerging high-field ultrashort pulse sources involve both strong deviation from paraxiality and ultrabroadband excitation. Consequently, systematically adding additional terms to NLSE in a self-consistent fashion should eventually fail.

The UPPE can be formulated in both a time- and z-propagated form. For the present purposes we present just the full vector z-propagated version that connects most naturally to the many nonlinear envelope models presented in the recent literature.

$$\partial_z \vec{E}^{\perp}_{k_x,k_y}(\omega,z) = ik_z \vec{E}^{\perp}_{k_x,k_y}(\omega,z) + \sum_{s=1,2} \vec{e}_s^{\,\perp} \vec{e}_s \bullet \left[ \frac{i\omega^2}{2\varepsilon_0 c^2 k_z} \vec{P}_{k_x,k_y}(\omega,z) - \frac{\omega}{2\varepsilon_0 c^2 k_z} \vec{j}_{k_x,k_y}(\omega,z) \right]$$

where

$$k_z \equiv \sqrt{\omega^2 \varepsilon(\omega)/c^2 - k_x^2 - k_y^2}$$

is the plane-wave propagation constant for angular frequency $\omega$ and transverse wavenumbers $k_x$, $k_y$. This z-propagated form of UPPE describes the evolution of spatio-temporal spectral amplitudes $\vec{E}^{\perp}_{k_x,k_y}(\omega,z)$ of the optical field along the propagation coordinate. The real total field amplitude $\vec{E}(x,y,z,t))$ is obtained by Fourier transforming the spectral amplitude at a fixed space point z. This UPPE has all of the linear absorption/dispersion properties lumped into the first term on the right and nonlinear polarization and current sources constitute the remaining terms. This equation encodes the complete linear optical response (absorption/dispersion) in the leading term on the right and can handle arbitrarily strong departure from paraxial behavior (extreme linear or nonlinear focusing down to $\sim\lambda$, for example). The nonlinear source terms are not discussed in detail here as it is the physically self-consistent formulation of these that represents a major thrust of the proposed effort.

For many practical applications the scalar version of this equation suffices

$$\partial_z E_{k_x,k_y}(\omega,z) = ik_z E_{k_x,k_y}(\omega,z) + \frac{i\omega^2}{2\varepsilon_0 c^2 k_z} P_{k_x,k_y}(\omega,z) - \frac{\omega}{2\varepsilon_0 c^2 k_z} j_{k_x,k_y}(\omega,z)$$

In this form, we can seamlessly derive the many nonlinear envelope models of the recent literature [Kolesik2004UPPE].

As an illustration we will derive NLSE and a recent nonlinear envelope equation (NEE) proposed by Brabec and Krausz in 1997[Brabec1997]. We assume no free charges and drop the last current source term. Writing z-UPPE in a compact form

$$\partial_z E_{k_x,k_y}(\omega,z) = iKE_{k_x,k_y}(\omega,z) + iQP_{k_x,k_y}(\omega,z)$$

where $K(k_x.k_y,\omega) = \sqrt{\omega^2\varepsilon(\omega)/c^2 - k_x^2 - k_y^2}$ is the linear field propagator in the spectral representation and

$$Q(k_x,k_y,\omega) = \frac{\omega^2}{2\varepsilon_0 c\sqrt{\omega^2\varepsilon(\omega)/c^2 - k_x^2 - k_y^2}}$$

will be called the nonlinear coupling term. We will have to make some simplifying assumption about the polarization in what follows in order to connect to familiar envelope models.

To obtain envelope equations we must express the electric and polarization fields in terms of envelopes by factoring out the carrier wave at a chosen reference angular frequency $\omega_R$ with corresponding wavenumber $k_R = K(0,0,\omega_R)$:

$$E(x,y,z,t) = A(x,y,z,t)\, e^{i(k_R z - \omega_R t)}$$

and similarly for the polarization $P$.

The procedure will be to Taylor expand the coefficients K and Q above and use the standard identities:

$$(\omega-\omega_R) \Leftrightarrow i\partial_t \quad ik_x \Leftrightarrow \partial_x \quad ik_y \Leftrightarrow \partial_y \quad \partial_z \Leftrightarrow ik(\omega_R) + \partial_z \ .$$

The classical NLSE equation follows by expanding the linear term K to second order in $(\omega-\omega_R)$ and $k_x, k_y$:

$$K(k_x.k_y,\omega) = \sqrt{\omega^2\varepsilon(\omega)/c^2 - k_x^2 - k_y^2}$$

$$\approx k_R + v_g^{-1}(\omega-\omega_R) + \frac{k''}{2}(\omega-\omega_R)^2 - \frac{1}{2k_R}(k_x^2 + k_y^2)$$

and ignoring completely the frequency dependence of the nonlinear coupling term Q i.e

setting $\omega = \omega_R$:

$$Q\left(k_x, k_y, \omega\right) = \frac{\omega^2}{2\varepsilon_0 c\sqrt{\omega^2\,\varepsilon\left(\omega\right)/c^2 - k_x^2 - k_y^2}} \approx \frac{\omega_R}{2\varepsilon_0 n\left(\omega_R\right)c}$$

In order that we recover the classical NLSE we make a simple assumption for the nonlinear polarization i.e assume an optical Kerr nonlinearity

$$P = 2\varepsilon_0 n\left(\omega_R\right) n_2 IA$$

Inserting these approximations into z-UPPE we obtain

$$\partial_z A = iv_g^{-1}\left(\omega - \omega_R\right)A + \frac{ik^{''}}{2}\left(\omega - \omega_R\right)^2 A - \frac{i\omega_R}{c} n_2 IA$$

Finally, Fourier transforming we obtain NLSE

$$\left(\partial_z + v_g^{-1}\partial_t\right)A = \frac{i}{2k_R}\Delta_\perp A - \frac{ik^{''}}{2}\partial_{tt}A + \frac{i\omega_R}{c} n_2 \,|\,A|^2\, A$$

The physical restrictions of NLSE are evident from this approximation procedure. Approximating K to second order in frequency and transverse wavenumber amounts to the paraxial and quasi-monochromatic approximation for linear wave propagation. The approximation that Q is a constant also requires a spectrally local interaction.

The nonlinear envelope model (NEE) derived by Brabec and Krausz in 1997 is widely used in the modeling of high power ultrashort pulse propagation problems. For completeness and as a contrast to NLSE, we derive this NEE model now.

We again approximate the linear propagator K by its paraxial version:

$$K\left(k_x.k_y, \omega\right) = \sqrt{\omega^2\varepsilon\left(\omega\right)/c^2 - k_x^2 - k_y^2} \approx k\left(\omega\right) - \frac{c}{2\omega n\left(\omega_R\right)}\left(k_x^2 + k_y^2\right)$$

This is essentially the same second order (paraxial) Taylor expansion in transverse wavenumber with some minor approximations. Namely, we replace $n\left(\omega\right) \to n\left(\omega_R\right)$ in the denominator of the diffraction term and thus, partly neglect chromatic dispersion. We retain the full linear dispersion and for convenience rewrite K so as to explicitly extract the group velocity term

$$k\left(\omega\right) = k\left(\omega_R\right) + v_g^{-1}\left(\omega - \omega_R\right) + D\left(\omega - \omega_R\right)$$

where

$$D(\omega-\omega_R)=\sum_{n=2}^{\infty}\left(\frac{\partial^n k}{\partial\omega^n}\right)_{\omega=\omega_R}\frac{(\omega-\omega_R)^n}{n!}$$

contains all higher order temporal dispersion terms.

We next approximate the nonlinear coupling term Q as:

$$Q(k_x,k_y,\omega)=\frac{\omega^2}{2\varepsilon_0 c\sqrt{\omega^2\,\varepsilon(\omega)/c^2-k_x^2-k_y^2}}\approx\frac{(\omega-\omega_R)+\omega_R}{2\varepsilon_0 cn(\omega_R)}$$

Putting these approximations back into z-UPPE we obtain

$$\partial_z A+iv_g^{-1}(\omega-\omega_R)A=iD(\omega-\omega_R)A$$
$$+\frac{ic}{2\omega_R n(\omega_R)}\left(1+\frac{\omega-\omega_R}{\omega_R}\right)^{-1}(k_x^2+k_y^2)A+\frac{i\omega_R}{2\varepsilon_0 cn(\omega_R)}\left(1+\frac{\omega-\omega_R}{\omega_R}\right)P$$

Finally, transforming to the real space representation

$$\partial_z A+iv_g^{-1}\partial_t A=iD(\partial_t)A+\frac{i}{2k_R}\left(1+\frac{i}{\omega_R}\partial_t\right)^{-1}\Delta_\perp A+\frac{ik_R}{2\varepsilon_0 n^2(\omega_R)}\left(1+\frac{i}{\omega_R}\partial_t\right)P$$

This is the NEE equation used extensively in ultrashort pulse propagation problems. It has the obvious advantage of including temporal dispersion to all orders but still ignores non-paraxial effects. Notice the appearance of the inverse operator coupling time and space – this is often truncated using a binomial expansion with potential disastrous consequences for the study of supercontinuum generation.

The class of problems that we intend to tackle in this proposal will generally involve strong non-paraxial, ultra-broadband propagation phenomena and truncated models such as the above are not relevant. Moreover, nothing has been said about how one approximates the induced nonlinear polarization or current source terms. Approximations made in the literature for these terms are even more severe and deriving better nonlinear source models represents a major proposal thrust.

## II. Success Stories of UPPE

We now briefly encapsulate some of the successes achieved to date using the UPPE propagator model. This model has been applied to femtosecond atmospheric light string propagation, simultaneous generation of supercontinuum and third harmonics in air and water, generation of nonlinear X-waves in normally dispersive and O-waves in anomalously dispersive condensed media and a reduced effective 1D model to study

supercontinuum shaping in sub-micron and photonic crystal fiber cores. These successes with rather naïve nonlinear dispersion models can be ascribed to the fortuitous dominance of the linear dispersion in each scenario. A goal of the present proposal will be to derive computationally feasible and physically self-consistent models that capture the full linear and nonlinear dispersive and absorptive properties of the relevant material system.

## II.1 Femtosecond Atmospheric Light Strings

Our group at the Arizona Center for Mathematical Sciences (ACMS) has played the lead internationally in establishing a robust theory and modeling of femtosecond light string propagation in air. The mechanism of nonlinear spatial replenishment was proposed by us in 1998 [Mlejnek1998] and shortly thereafter, experimentally confirmed by the group in Laval, Quebec. It was proposed by us at the time that the persistent nonlinear chaotic generation of intense light strings, accompanied by plasma channels could be identified with the broad pulse background acting as a reservoir that feeds individual critical self-focusing events within the much broader pulse. While the initial pulse waist is on the order of centimeters, individual light strings have diameters on the order of 100 μm and the dilute plasma channels generated by the light strings even smaller 50 – 80 μm diameters. Our initial model for light string generation was a generalized NLSE equation coupled to a Drüde plasma model. This model proved important in isolating the role of various physical mechanisms operative during the initial nonlinear interaction over a few meters. We were very much aware at the time that this NLSE model had some serious drawbacks. For example, its narrowband (slowly varying envelope) limitation raised concerns about properly describing supercontinuum generation and we moved on to deriving UPPE. Of equal concern however was that we were describing the nonlinear interaction terms by fixed wavelength pre-computed optical Kerr coefficients and multiphoton cross-sections – yet the ultra-broadband generated supercontinuum has spectral intensities in the 10's of GW range that are fully consistent with strong nonlinear coupling. UPPE solved the former problem but the latter remains open as we need quantum mechanical models of the light-matter interaction – the latter are as computationally as intensive or more so than the EM propagation equation. One fundamental question that has not been resolved in experimental femtosecond light string propagation studies is the appearance of a

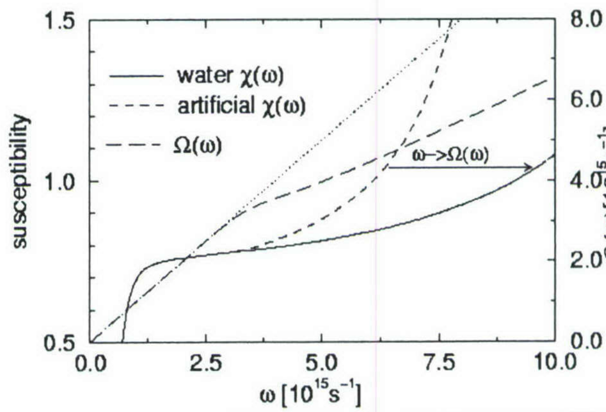


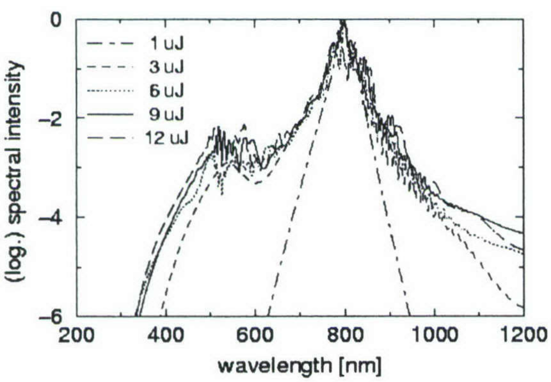

**Figure 2** Real water susceptibility and an artificially constructed susceptibility that departs for the real at high frequencies well outside the initial pulse spectral bandwidth.

relatively quiescent regime with weak plasma generation subsequent to the initial violent critical collapses. Experiment indicates that the light strings seem to stay collimated even though there appears to be no indicator of plasma generation i.e detectable THz signals. This is consistent with some form of saturation of the optical Kerr effect. We have very preliminary evidence from full quantum mechanical solutions of hydrogen-like atoms that such a saturation effect is real [Kano2006]. Hence, although many of the qualitative features can be understood with realistic linear dispersion and non-dispersive nonlinear effects, this latter important observation must be ascribable to a nonlinear dispersive response.

Using UPPE we were able to show that the spectral extension of super-continuum generation about the reference pulse frequency is a very sensitive function of the linear material dispersion at spectral locations far removed from the initial pulse spectrum. We performed comparative simulations in water and gases to reveal the mechanism that controls the supercontinuum extent and its dependence on the medium band-gap [Kolesik2003PRL: Kolesik2003APB].

Figure 2 shows two linear material susceptibilities for water and an artificial, water-like medium. These were chosen such that the bulk of the SC-generating pulse propagated essentially unchanged. Figure 3 shows on the left how the spectral broadening depends on input pulse energy. On the right, we show that the modification of the real part of the dielectric susceptibility far away from the influence of the exciting pulse bandwidth can significantly alter the spreading of the generated SC. This implies a strong sensitivity to the linear dispersion landscape.

These simulations allowed us to correct and extend the so far accepted scenario for SC generation and its dependence on the medium band-gap. An effective three-wave mixing paradigm, [Kolesik2004PRL] that can be used to explain qualitatively a number of effects in femtosecond pulse propagation in general, also emerged as a product of our qualitative simulation studies.



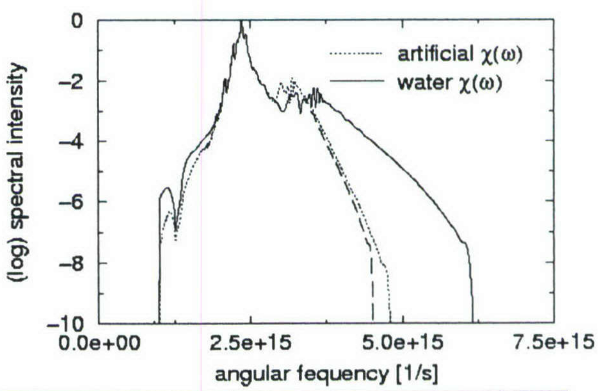




**Figure 3** Left: Measured spectral superbroadening in water as a function of increased pulse energy. Right: Spectral extent of the generated supercontinuum with and without the artificial water susceptibility response.

## II.2 Supercontinuum and Third Harmonic Generation

More recently we succeeded in reproducing experimental results showing simultaneous SC and THG generation in air under weak and strong linear focusing conditions. By using a short focal length lens, all nonlinear effects occur near the localized high intensity focal spot making nonlinear propagation effects less important. Consequently, the generated SC was localized in frequency and both fundamental and THG spectral components remained essentially decoupled during propagation. These results are shown in Figure 4.

The very strong intermixing of fundamental and third harmonic components on the right in Figure 4 makes it unlikely that a classical slowly-varying individual FF and TH envelope field approach will work.

Our simulations were the first to include TH and SC generation in a unified, self-consistent way [Kolesik2006]. Our results make it possible to correct some previously published conclusions. In particular, we have shown that the SC generation mechanism is independent of the TH generation mechanism, though both effects are controlled by the same underlying effective three-wave mixing processes [Kolesik2004PRL]. We have also shown that it is possible to clearly distinguish experimentally the origin of the high-frequency radiation in the far-field spectrum even when the TH and SC components appear to merge as illustrated in Figure 4.

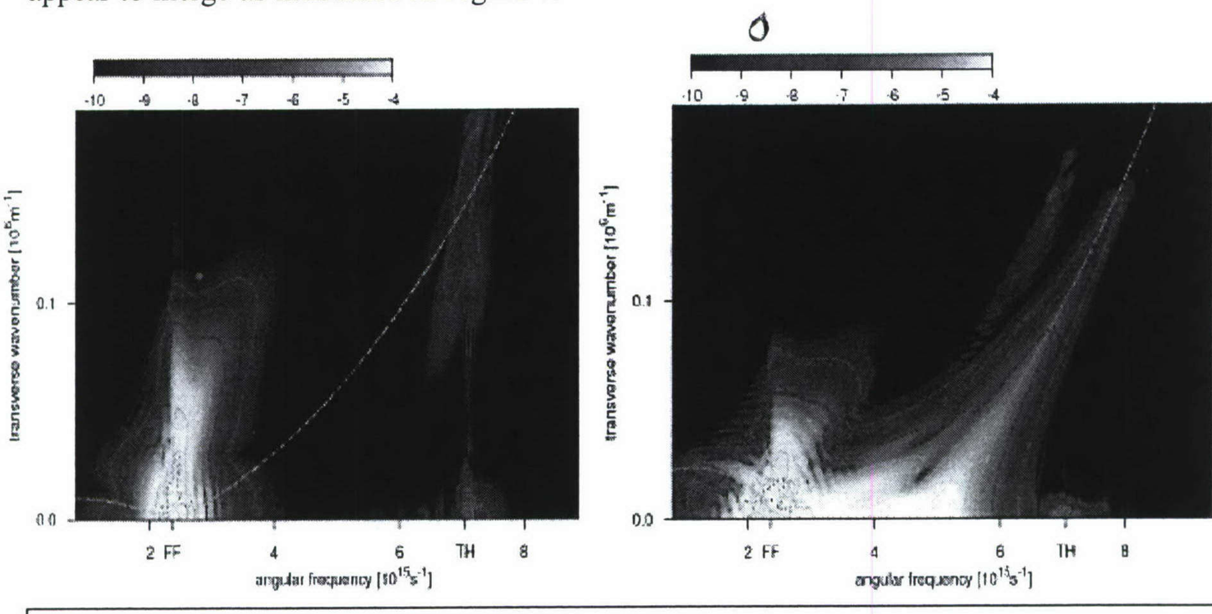



**Figure 4** Left: On- and off-axis emission spectra for a tightly focused intense femtosecond pulse in water. The fundamental (FF) and third harmonic (TH) don't overlap spectrally. Right: Strongly admixed FF and TH spectral components due to strong SC generation subsequent to critical collapse in weakly focused geometry.

## II.3 Nonlinear X- and O-Waves in Water

The subtle interplay between critical collapse (self-focusing) and normal/anomalous dispersion in condensed media has been spectacularly demonstrated in a series of important experiments by a group in Como, Italy. By loosely focusing an intense femtosecond pulse in water, they observed a very strong X-feature in the spectrally resolved far-field of the trapped pulse when the carrier wavelength was such that the material exhibited normal dispersion. More recently, nonlinear O-waves were observed by the same group when the central pulse wavelength was chosen to correspond to anomalous material dispersion. These propagation phenomena are illustrations of

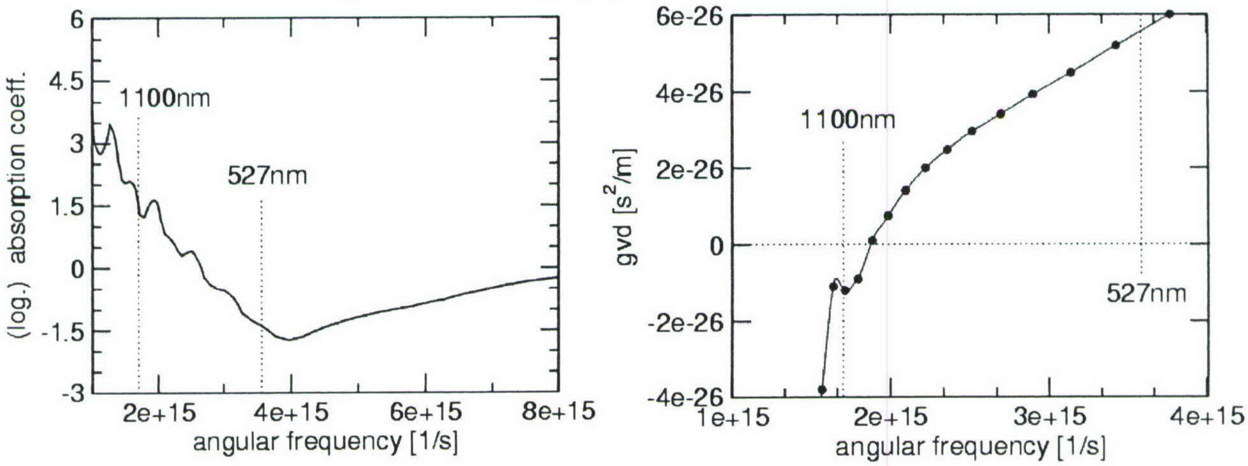



Figure 5 The z-UPPE takes as input the entire absorption and dispersion spectral landscape shown on the left and right, respectively. The numerical algorithm senses all physical values over the spectral range

strongly non-paraxial propagation requiring accurate resolution of off-axis propagating components of the propagating pulse. The measured input absorption and dispersion data for water are shown in Figure 5. Our work showed that the propagating pulse exhibited extremely complicated spatio-temporally chaotic bursts giving the illusion of a stationary self-trapped nonlinear waveguide in water. What is remarkable is that the spectrally-resolved far-field exhibits a pronounced X-feature implying the existence of a universally

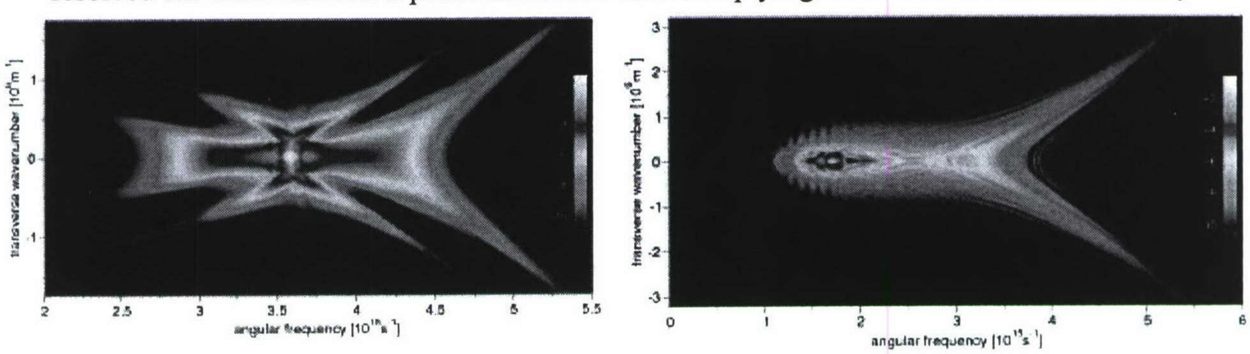


Figure 6 Left: Spectrally resolved far-field for a pulse where the initial and generated SC is located entirely within the normally dispersive region. Right: The pulse spectrum lies in the anomalously dispersive region but the generated spectrum extends into the normally dispersive regime.

attracting asymptotic set in the infinite degree of freedom problem. Figure 6 shows a graph of the X-wave and O-wave feature. The O-wave is polluted by some X-wave character in the right picture because the generated SC extends across into the normally dispersive regime.

## II.4 Self-healing filaments and the role of the low-intensity background

Computer simulations contributed crucially to the present understanding of femtosecond light strings in air and other gaseous media as well as in condensed matter. One particularly important observation, made for the first time by our group [Mlejnek1999] several years ago, is that the high-intensity light strings exchange their energy with the reservoir of the low-intensity background of the pulse. Thus, the low-intensity background provides the mechanism necessary for multiple hot filaments to survive over large distances.

More recently, an experiment [Courvoisier2003] suggested that even a single filament is extremely robust with respect to its interaction with water droplets (for example in clouds). We have applied our UPPE simulator to reveal for the first time that it is actually the low-intensity background, forming a pedestal surrounding the central hot spot, that is the cause for the filament robustness. We have shown that filaments, after being temporarily destroyed in the center by collision with a water droplet, heal themselves over very short distances. This self-healing process is driven by the optical energy stored in the low-intensity background [Kolesik2004SH]. Note that similar results were later published independently by another group [Skupin2004].

This insight, brought by simulation, provided the theoretical basis for understanding a subsequent open-air experiment [Mechain2005] demonstrating that femtosecond light strings can propagate even in clouds and rain.

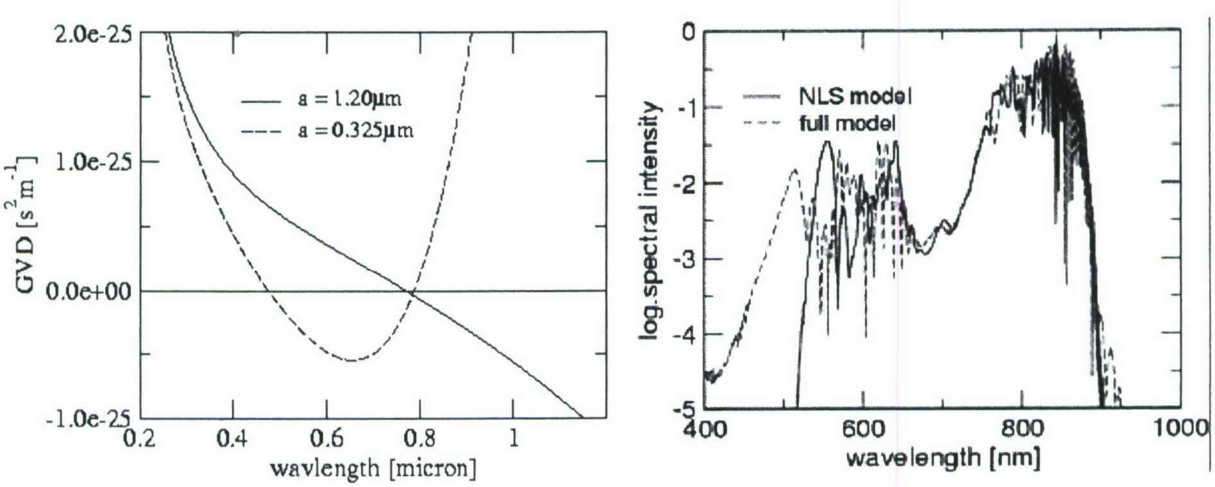



**Figure 7** Left: Calculated group velocity dispersion (GVD) for silica fibers with two different core diameters: a=1.20 μm and a=0.325 μm. Right: Generated white light continuum using an NLS model and the UPPE model.

The role of the low-intensity background has since been corroborated in several experimental and theoretical studies [Dubietis2004: Liu2005: Ackermann2006: Gaizauskas2006].

### II.4 Shaping the super-continuum in sub-micron and photonic crystal fibers

This application of UPPE takes advantage of the very accurate representation of white-light super-continuum over huge spectral windows. The problem can be reduced to a 1D simulation due to the strong confinement of the light within the fiber core. Figure 7 shows an example of how the fiber group velocity can be engineered by tapering a conventional silica fiber such that the fiber core is reduced to a sub-micron diameter. The resulting GVD landscape is significantly modified with two zeroes of GVD occurring for the smaller core fiber [see Figure 7 Left]. The right hand side of this figure shows a comparison of the white-light super-continuum obtained by using a generalized NLSE model (that includes accurate chromatic and waveguide dispersion) and the present UPPE model.

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## Project Publications

**1. M. Kolesik, J.V. Moloney, G. Katona and E.M. Wright**
***Theory and Simulation of Supercontinuum Generation in Transparent Bulk Media***
*Applied Physics B.*, **77**, pp. 185-195, (2003)

**2. M. Kolesik, J.V. Moloney, G. Katona and E.M. Wright**
***Physical Factors Limiting the Spectral Extenet and Band Gap Dependence of Supercontinuum Generation***
*Physical Review Letters*, **91**, No. 4, (2003)

**3. M. Kolesik, J.V. Moloney**
***Self-healing femtosecond light filaments***
*Opt. Lett.***29, 590**,2004.

**4. M. Kolesik, E. M. Wright, J. V. Moloney**
**Simulation of femtosecond pulse propagation in sub-micron diameter tapered fibers**
Applied Phys. B 79, 293-300, 2004

**5. A.R. Zakharian, J.V. Moloney and M. Mansuripur.**
***Transmission of Light Through Small Elliptical Apertures***
*Optics and Photonics News*,15 (3) pp **38-43**, 2004.

**6. M.Kolesik, E.M.Wright, J.V. Moloney,**
***Dynamic nonlinear X-waves for femtosecond pulse propagation in water***
*Phys. Rev. Lett.***92,253901**,2004.

**7. M. Kolesik, J.V. Moloney**
***Nonlinear optical pulse propagation: From Maxwell's to unidirectional equations,***
*Phys. Rev E.* **970, 036604**,2004.

**8. Yong Xie, A.R.Zakharian, J.V.Moloney, M.Mansuripur**
***Transmission of light through slit apertures in metallic films***
*Optics Express, Vol 12, No.25*,pp **6106-6121** , 13 December,2004.

**9. W. Hoyer, J.V. Moloney, E.M. Wright, M.Kira, and S.W. Koch *Thermal Wakefield Oscillations of Laser-Induced PLasma Channels and their Spectral Signatures in Luminescence***
Journal of Physics: Conference Series 11, 153 (2005)

**10. W. Hoyer, A. Knorr, J.V. Moloney, E.M. Wright,M. Kira, S.W. Koch**
***Photoluminescence and Terahertz Emission from Femtosecond Laser-Induced Plasma Channels***
Phys. Rev. Lett. 94, 115004 (2005)

**11. M. Richter, M. Schaarschmidt, A. Knorr, W. Hoyer, J.V. Moloney, E.M. Wright, M. Kira, and S.W. Koch *Quantum Theory of Incoherent THz-Emission of an Interacting Electron-Ion Plasma***
Phys. Rev. A 71, 053819 (2005)

**12. C. Dineen, J. Forstner, A.R. Zakharian, J.V. Moloney, S.W. Koch,**
**" Electromagnetic field structure and normal mode coupling in photonic crystal nanocavities"**
Optics Express 13, 4980 (2005)

**13. T. A. Niday, E. M. Wright, M. Kolesik, and J. V. Moloney, "Stability and transient effects for nanosecond ultraviolet light filaments in air,"**
Phys. Rev. E 72, 016618 (2005).

**14. M. Kolesik, E. Wright, and J. Moloney, "Interpretation of the spectrally resolved far field of femtosecond pulses propagating in bulk nonlinear dispersive media,"** Optics Express 13, 10729-10741 (2005)

**15. Teipel J., Turke D., Giessen H., Killi A., Morgner U., Lederer M., Kopf D., Kolesik M.: " Diode-pumped, ultrafast, multi-octave supercontinuum source at repetition rates between 500 kHz and 20 MHz using Yb : glass lasers and tapered fibers"**
Optics Express 13 (2005) 1477-1485

**16. Y. Xie, A. Zakharian, J. Moloney, and M. Mansuripur, "Transmission of light through a periodic array of slits in a thick metallic film,"** Opt. Express 13, 4485-4491 (2005)

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*Opt. Express 14, 6400-6413 (2006)*

**18. A. R. Zakharian, P. Polynkin, M. Mansuripur, and J. V. Moloney, "Single-beam trapping of micro-beads in polarized light: Numerical simulations,"** *Opt. Express 14, 3660-3676 (2006)*

**19. D.E. Roskey, E.M. Wright, M. Kolesik, J.V. Moloney**
**The role of linear power partitioning in beam filamentation**
*Appl. Phys. B (to appear) 2006*

**20. M. Kolesik, E.M. Wright, A. Becker and J.V. Moloney**
**Simulation of third-harmonic and supercontinuum generation for femtosecond pulses in air**
*Appl. Phys. B (to appear) 2006*

**21. P.O Kano, M. Brio and J.V. Moloney " Numerical analysis of the ab initio computation of the effects of ionization on the nonlinear susceptibility coefficients of the hydrogen atom"**
Comm. Math Sci. **4**(2006) 53-80

**22. A.R Zakharian, M. Brio and J.V. Moloney, "Second order accurate FDTD space and Ttme grid refinement method"**
IEEE Phot. Tech. Letts., 2006.

## Books and Book Chapters

1. Jerome V Moloney and Alan C. Newell, "Nonlinear Optics" (Perseus Press: Second Edition) 2004
2. J.V. Moloney and M. Kolesik, "Full Vectorial, Intense Ultrashort Pulse Propagators: Derivation and Applications" Book Chapter to appear in "Progress in Ultrafast Intense Laser Science" Volume II, (Springer) 2006.

## Awards to PI

1. Fellow of the Optical Society of America - 2004
2. Humboldt Prize in Physics - 2005

# Interactions/Transitions

## Invited Talks and Lectures

J.V. Moloney, Contemporary Photonics Lecture Series "Ultrashort pulse propagation: Light strings and associated phenomena", Friedrich-Schiller University Jena Germany, May 29 2006.

J.V. Moloney, Invited talk: "Full vectorial ultrashort unidirectional pulse propagators", European Foundation for Research and Technology (FORTH), Crete, Greece May 24, 2006.

J.V. Moloney, Plenary Speaker "Full vectorial, ultrashort unidirectional pulse propagators" at the Advanced High Power Laser Ablation conference, Taos, May 7-12 2006.

J.V Moloney, "Intense ultrashort probes of matter: Theory and applications", Alexander von Humboldt Prize lecture, University of Marburg, February 2006.

J.V Moloney, "Intense ultrashort probes of matter: Theory and applications", University of Paderborn, February 2006.

E.M. Wright: "Laser light strings for atmospheric propagation," SPIE, Orlando April 2006.

J.V. Moloney: Invited Tutorial Lecturer: Seminar and Workshop on Intense Field Laser-Matter Interaction and Pulse Propagation", Max Planck Institute for Complex Systems", August 1-24, 2005, Dresden, Germany

J.V. Moloney: Invited paper, "Modeling Optical Structures" OSA Annual Meeting Frontiers in Optics, Tucson, Oct 16-20, 2005.

J.V. Moloney: Invited paper "AMR FDTD solver for nanophotonic and plasmonic applications" Photonics Europe, Strasbourg, France, April 26-30, (2004)

J.V. Moloney, Colloquium "Ultrafast Nonlinear Optics, femtosecond light strings, nonlinear X-waves and Supercontinuum Control", Technical University of Berlin, July 2004.

J.V. Moloney: Invited paper, "Computational Nanophotonics" ETOS Cork, Ireland, July 26-29, (2004).

J.V. Moloney: Invited paper " Nonuniform and Adaptive Mesh FDTD Simulation Tools for Optical Data Storage Applications " at the International Symposium on Optical Memory (ISOM), Nara, Japan Nov 3-7, 2003

J.V. Moloney: Invited paper "Physics and Simulation of light string propagation", Frontiers in Optics, Optical Society of America, Tucson, AZ Oct. 5-9, 2003.

J.V. Moloney: Invited paper "Role of Long Wavelength Energy Reservoir in Generating and Sustaining Femtosecond Atmospheric Light Strings", International Symposium on Ultrafast Intense Laser Science, Manoir du Lac Delage, Quebec, Canada, Sept. 25-30, 2003.

## Transitions

USAF Captain Thomas Niday completed his Ph.D degree in Optical Sciences on July 15, 2004 while working directly on this project. Captain Niday is currently at AFIT.

## Personnel Supported on the Project:

**Senior Researchers**
Professor J.V Moloney – Principal Investigator
Professor E.M. Wright – Co-Principal Investigator
Professor J.-C Diels – Co-Principal Investigator (UNM)
Professor M. Brio – Co-Principal Investigator
Research Associate Professor M. Kolesik – Co-Principal Investigator
Dr. James Murray – Consultant
Professor A. Knorr – Visiting Faculty

**Postdoctoral Fellows:**
C. Dineen – Ph.D Computer Science
W. Hoyer – Ph.D Theoretical Physics
M. Reichelt – Ph.D Theoretical Physics
A Zakharian – Ph.D Lunar and Planetary Sciences
Y. Kaneda – Ph.D – Electrical Engineering
J. Hader – Ph.D – Theoretical Physics
D. Kouznetsov – Ph.D Physics

**Graduate Students:**
Patrrick Kano – Ph.D Applied Mathematics 2005.
Gregory Katona – Optical Sciences Ph.D student
K. Mohan Gundu – Optical Sciences Ph.D student
H. Li – Optical Sciences Ph.D student
Y. Xie – Optical Sciences Ph.D student
R. Abdul Malik – Optical Sciences M. Sc student parttime
Z. Wang – Physics student partime